CLEANING TURBOMACHINERY WITHOUT DISASSEMBLY, ONLINE AND OFFLINE

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ABSTRACT

Turbomachinery is designed for optimum aerodynamic and mechanical performance at given user conditions. Before shipment, this performance is usually verified on the OEM's test floor, based on specified design conditions. However, in operation, the gas composition can vary and include unanticipated solid and liquid ingestion into the turbomachinery, causing a buildup of foreign materials. The resulting fouling has an adverse effect on aerodynamic and mechanical performance of the unit. Fouling comes from external dust, dirt or dissolved matter, process materials, condensation and/or chemical reactions. Depending on the rate and composition of the deposits, the effect could range from a fast buildup, causing immediate shutdown of the unit due to high vibration and possible parts damage, to a slow buildup causing increased vibration and/or reduction in performance. An overview is presented of the cause, effect, and prevention of fouling on turbomachinery, with its main purpose to present tested and proven methods of cleaning turbomachinery. Presented are methods of online and offline (without disassembly) cleaning of multistage centrifugal compressors, axial compressors, and steam turbines. The operating environment will encompass hydrogen recycle gas, steam, and air. Methods include online cleaning using saturated steam, liquid spray and abrasive solids, and offline cleaning using acidized saturated steam for turbines and crank-washing for compressors.

INTRODUCTION

Maintaining peak performance in operation is important to ensure long term reliability of turbomachinery. Turbomachinery is designed to meet specific criteria required by the user. For compressors, this means providing required head and flow at given inlet gas conditions, and for turbines, providing shaft power output at given steam conditions. The turbomachinery engineer must make assumptions when designing machines to meet given specifications, primarily that the gas handled by the proposed equipment will 1) be free of liquid and solid contaminants including dissolved materials; 2) be a homogeneous gas (no condensation) throughout the unit; 3) have no chemical reactions forming liquid or solid residue, prior to or within the unit; and 4) not corrode the blades or flow passages. A clean flowpath design normally meets performance requirements, as demonstrated on the OEM's test floor and/or at the initial start up of the unit. However, in operation the gas, air, or steam handled by turbomachinery can change composition or conditions and cause one or more of the four "C" problems: Contamination, Condensation, Corrosion, and Chemical reaction. Eventually, one or more of the four "C"s can cause problems by building up on the blades and passageways or wearing down the blades by erosion and/or corrosion. The user may see performance of the unit drop off, shaft vibration increase, or, if not caught in time, a unit trip with possible parts damage.

The purpose herein is to help the reader identify causes and results of buildup in turbomachinery flowpath and methods that can correct the problem without shutdown or disassembly of the unit. Case histories are presented, using the methods described in the paper. The first case is a multistage steam turbine that had sodium buildup on blades and flow passages, and was cleaned online by dropping the steam temperature to saturation at speed. The second turbine case is a low speed cleaning of a multistage turbine that had problems with sodium and silica buildup. There are two case histories of multistage hydrogen recycle compressors. One had a severe problem with chloride deposits and the other with ammonium salt deposits. Also presented are online methods to clean axial compressors.

The described methods and techniques address the symptoms of a problem. It must be emphasized that the user must determine the *cause* of the problem, and may need assistance of the turbomachinery OEM. In many cases, it may be a sound decision to ignore correcting the cause, and treat the symptoms as they occur. Case in point, an axial compressor with a 10 micron inlet filter has buildup occurring within the flowpath over a long period of time. Since the fix, in most cases, is simply ricing the unit, there is no economic justification for more stringent filtration requirements. In other situations, the cause of the problem must be properly identified and corrected, as will be shown in the recycle compressor case. The user should be careful not to get sidetracked by a symptom. An example would be concentrating on and even changing the rotordynamics of a unit to reduce high vibration readings instead of recognizing and correcting the real problem of buildup on the impeller. The user should know the root cause of performance and mechanical problems, especially on critical machines, so optimum decisions can be made to maintain peak performance and long term reliability of the turbomachinery.

STEAM TURBINE CLEANING

Online Cleaning

Very often in refineries, the quality of steam generated in boilers is not optimal. The steam will often contain dissolved salts, primarily sodium and ammonium chloride, which, under the right conditions, will precipitate out as solids in several places in the steam system including the trip valve and governor valve stems, turbine nozzles, and rotor blades. The result of these salts forming, is that steam passages through nozzles and rotor blading become plugged and surfaces become rough creating higher pressure drops thus the turbines lose performance. In addition, trip and governor valves become seized because of the deposition of salts between the stems and guides. The need for a turbine wash becomes apparent when the first stage steam pressure rises to above the manufacturer's limits and when the turbine can no longer provide enough power for the driven machine and begins to lose speed.

Since the salts that form in steam turbines are for the most part soluble in water, washing the machine is very effective in removing these salts and restoring performance. The problem is shutting the machine down to do a wash is costly since the refinery or at least the unit throughput is reduced while the wash is being done. Very often, a wash is required at three to four month intervals. This led to an investigation of the possibility of washing turbines at speed with wet steam. It was believed that if wet steam could be put through the turbine, the salt deposits would dissolve and the turbine performance would be restored. The most convenient way to get wet steam was to inject water into the steam some distance upstream of the turbine to be washed, in quantities that would reduce the temperature of the steam to close to saturation.

The main risk to dropping the steam temperature is having a difference in thermal growth rate between the stator and rotor during the wash process that could result in contact. A lesser risk was having impingement of droplets on the nozzles and blades which over a period of many washes could cause erosion of these parts.

Before the procedure was used for the first time, it was determined, by calculation, that injection of water at a rate of about 10 gpm into the steam line would reduce the temperature to 50°F above saturation. This machine operated at 750°F at 650 psig. and the injection of approximately 10 gpm of water at 200°F and 14.7 psia would reduce the temperature of the inlet steam to 550°F. The rate of water injection was calculated by the equation:

$$Q = \frac{G}{SG \times 500} \times \frac{hi - ho}{ho - hw}$$

Where: Q = Quantity of water injected in gpm
SG = Specific Gravity of the Steam
G = Steam flow in lb/hr
hi = Enthalpy of the Steam
ho = Enthalpy of cooled Steam
hw = Enthalpy of the water injected

At the conditions above the equation becomes:

$$Q = \frac{48{,}000}{0.965 \times 500} \times \frac{1290 - 1275}{1275 - 182}$$

$$= 10.5 \text{ gpm.}$$

Although desuperheating nozzles are available commercially, a nozzle was designed and built at the refinery and installed in the steam line about 50 ft upstream of the turbine at a blind TEE connection. The nozzle was designed to sit in the center of the steam line and point downstream with the steam flow (Figures 1 and 2).

The Washing Procedure

A team, made up of representatives from Operations, Maintenance, and Engineering met and jointly prepared the procedure for washing the turbine. It was agreed that the most important aspect of the wash was to reduce the steam temperature at a slow enough rate so that the change in temperature of the rotor and stator would be the same. After performing several calculations, it was agreed that a rate of 2.0°F/min would allow both stator and rotor to stay at the same temperatures.

The injection of water was to be done with a truck mounted engine driven triplex plunger pump that was sized slightly higher than the required 10 gpm. The pump would take steam condensate from a tank also mounted on the trunk. Since the pump was a constant flow machine, the rate of injection would be controlled by manually directing the excess flow to the storm sewer through a globe valve (A) and adjusting the flow from the pump by means of a needle valve (B) (Figure 3). It was agreed that the steam temperature, the salt or chloride level at the turbine outlet, the first stage pressure, the machine vibration levels and the bearing temperatures would all have to be closely monitored during the wash process in order to ensure the integrity of the machine and to determine when the machine was clean.

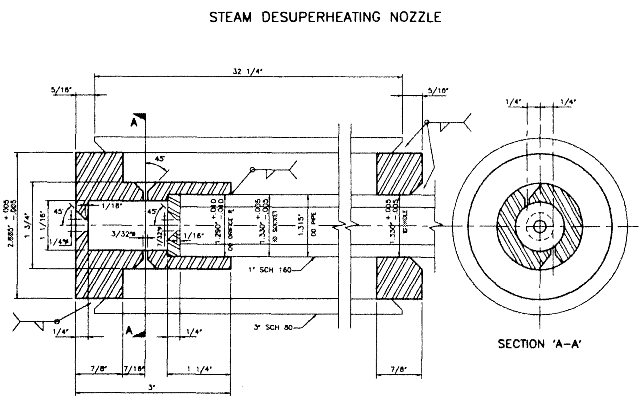

Figure 1. Desuperheating Nozzle Arrangement.

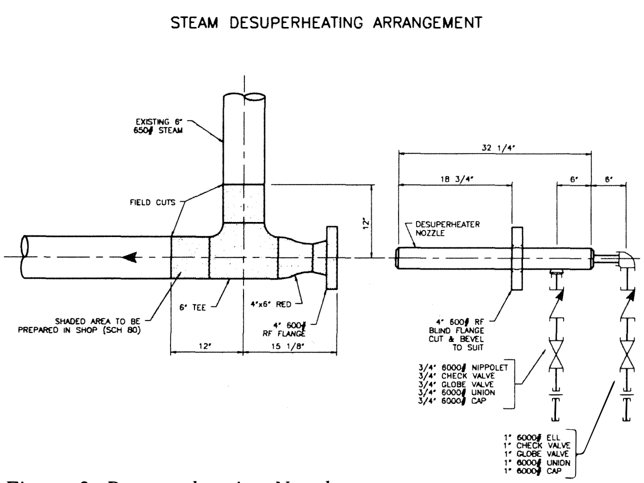

Figure 2. Desuperheating Nozzle.

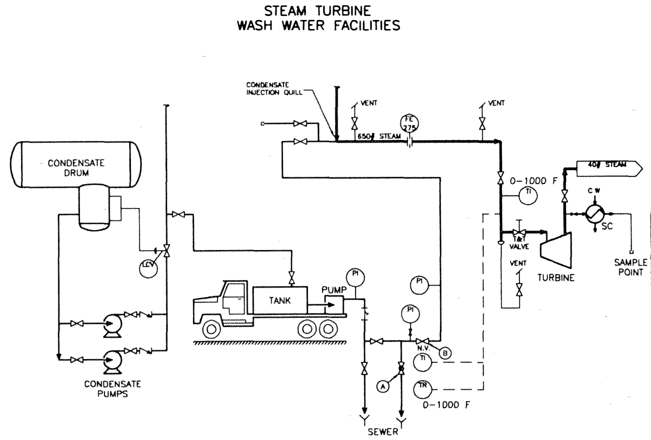

Figure 3. Steam Turbine Water Wash Facilities.

To achieve this the following was done:

- *Steam Inlet Temperature.* A thermocouple mounted in an already existing thermowell just upstream of the turbine was connected to a strip chart recorder located at the pump station where the operator could monitor the temperature while controlling the water flow.
- *Salt (Chloride) Levels.* An existing condensate sample point on the turbine outlet was used to collect condensate samples, which were then tested for chloride levels. The Chloride test was used as it was easy to do in the field test lab. The sample point was comprised of a stainless steel tube run from the turbine outlet pipe to grade where it was wound into a coil and placed in a bath of cold water to condense the steam.
- *First Stage Steam Pressure.* A pressure gauge mounted at the machine was used to monitor changes to the first stage steam pressure.
- *Vibration Levels.* Since the permanent vibration monitor was mounted in the control panel adjacent to the machine, it was used to monitor the vibration levels and axial position.
- *Bearing Temperatures.* All the bearing temperatures were recorded on a strip chart recorder mounted in the control panel at the machine. Both radial and thrust bearing temperatures remain fairly constant throughout the wash, but need to be closely monitored, especially on the first wash.

One operator was stationed at the turbine where he monitored the first stage steam pressure, the vibration levels and the bearing temperatures. If any rapid changes or abnormally high levels in these readings occurred, the pump operator would be contacted and the procedure would be halted. A log of steam flow, inlet temperature, turbine speed, first stage pressure, chloride level, vibration level and bearing temperatures would be kept throughout the wash.

Emergency Plan

It was agreed that in the event of a loss of condensate flow the turbine would be allowed to return to normal operating conditions before attempting to start injection of condensate again. If the inlet steam temperature began to decrease at faster rates than the prescribed 2.0°F/min the machine would be tripped. If vibration levels increased to "danger levels," or if any of the bearing temperatures increased to higher than 200°F, the machine would be shut down and the wash finished while shut down.

Washing the Turbine

Once all the instruments are connected and their calibration checked, the water tank on the truck is filled with steam condensate from the condensate drum. The pump is then started with the full flow being directed to the sewer. The globe valve (A) is then slowly closed until the pump discharge is at 1100 psig. The needle valve is then cracked open to allow the flow of condensate to go the to 650 psig steam line. As this is done, the steam temperature is very closely monitored, so that the rate of change of the temperature does not exceed the prescribed 2.0°F/min. Once a flow is established, the condensate pressure is maintained by throttling the globe valve (A).

As the injection of water continues, the first stage pressure, turbine vibration levels and the bearing temperatures are monitored to ensure that they do not exceed alarm levels. When the steam temperature falls below 600°F, the operator begins taking turbine outlet condensate samples and tests them for chloride levels. These begin to climb to a maximum level as the steam temperature reaches 550°F and then fall off very quickly to zero (Figure 4). At the same time, the first stage pressure drops to close to design levels. Both of these things indicate that the turbine is clean. The first stage steam pressures before and after the wash are plotted on the manufacturer's operating chart (Figure 5) and it can be shown that the wash makes a significant improvement to the machine efficiency.

Once the turbine is clean, the injection of water is reduced to allow the steam temperature to return to normal (750°F). As with the lowering of steam temperature, the increase is controlled to 2°F/min to maintain both rotor and stator at the same temperature (Figure 6).

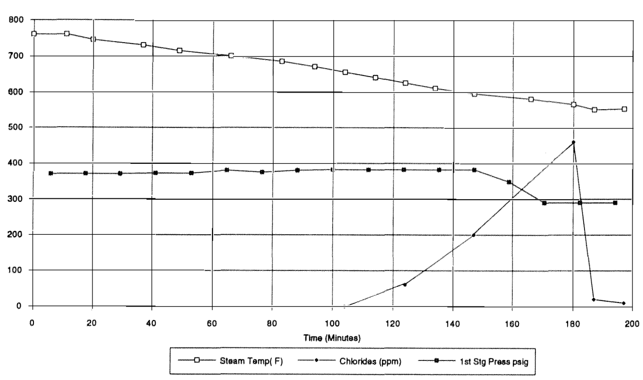

Figure 4. Changes in Steam Temperature, Chloride Levels and First Stage Pressure with Time During Wash.

The whole wash process takes about four and a half hours. At one location, this procedure has been used on four turbines about every four to six months for the last 14 years without a problem of any kind.

Offline Cleaning

Case two in the steam turbine section, discusses offline cleaning procedures. Online cleaning is always the preferred method, since it does not require shutting down the unit, but there are some situations that do not lend themselves to online cleaning. This case history falls into that category. Background on the case is:

- Service: Cat Cracker Air Blower
- Size: Elliott 70M (2)

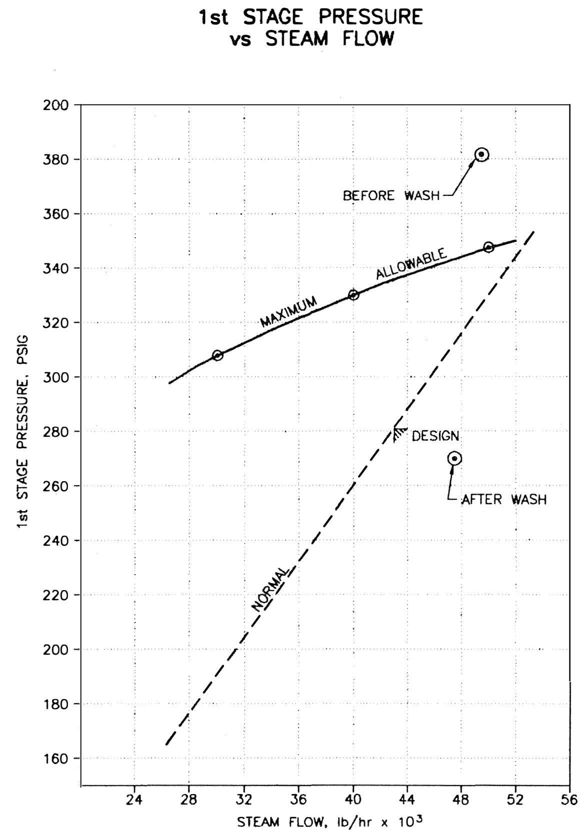

Figure 5. First Stage Pressure vs *Steam Flow.*

- Drivers: Elliott Steam Turbines, QV-8 and QV-6
- Horsepower: QV-8—4800, and QV-6—5100
- RPM—4900
- Operation Mode—Parallel

The QV-8 turbine typically operates at full admission valve and is horsepower limited, this typically sets the rate for the QV-6 turbine. Because of this power limitation, it is critical to clean the turbines when fouling starts in order to maintain unit charge rate. The buildup in the turbines was usually the same material and patterns. The nozzle ring and first two or three stages would be of a whitish color (sodium). In the cooler stages, the fouling would change to a darker color (silica). These two different deposits result from two different mechanisms. The sodium appeared to come from steam drum carryover and the silicon a result of water impurities.

The turbines cannot be online cleaned, because the power generated at saturated steam conditions could not maintain the compressor in parallel operation with the other compressor. Previously, the cleaning procedure was to operate the cat cracker at half load with the one string while the other turbine was being cleaned. The turbine being cleaned was taken offline and mechanically cleaned. The cleaning process would take about four days. The best solution would be to resolve the cause of the contamination, but this would be a costly project. The next best solution was to develop a procedure for cleaning the turbines without dismantling and mechanically cleaning. The following procedure was developed for offline cleaning.

Responsibilities:

- Operations—Operate steam and condensate/vinegar injection. Adjust blower discharge pressure.

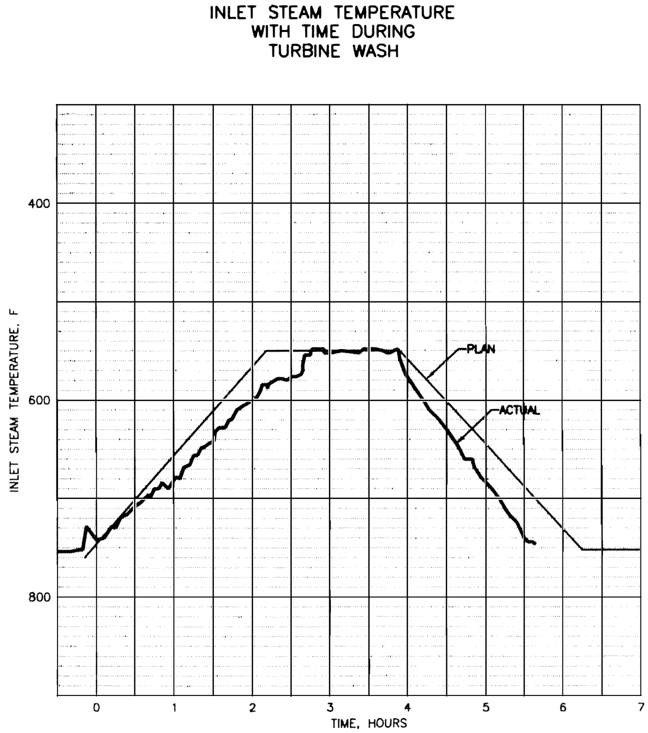

Figure 6. Inlet Steam Temperature with Time During Turbine Wash.

• Machinists—Monitor machine "health" throughout the procedure.

• Tech Services—Monitor steam quality at desuperheater. Monitor condensate conductivity.

Prior to starting the cleaning procedure, mix three drums (55 gal each) of 12 percent distilled white vinegar with 825 gal of condensate in a storage tank to obtain 990 gal of 2.0 percent vinegar solution. Refer to Figure 7 for a schematic of the piping arrangement described in the following procedure.

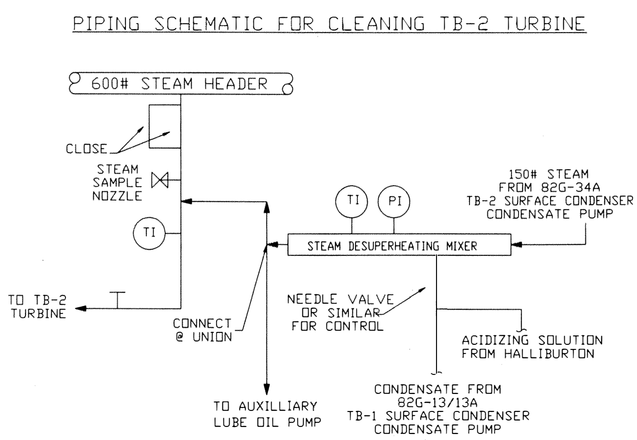

Figure 7. Piping Schematic for Offline Cleaning Turbine.

Step 1. Isolate the TB-2 turbine from the 600 psig steam header at the root valve and warm up bypass above blower shelter roof. Shut off steam to the inter and after jets.

Step 2. Connect 150 psig steam and condensate/vinegar injection per attached diagram.

Step 3. Start 150 psig steam to the turbine inlet. Notify the Waste Water Treatment Plant and Shift Foreman and divert condensate from the surface condenser to the sewer. Quench with fire water if necessary to maintain 100°F max sewer temperature. Target 1000 to 1200 rpm. Adjust the 150 psig steam valve at the surface desuperheating mixer to open all six ports of the emission rack. Pinch the waste air valve to obtain ~10 psig at the blower discharge.

Step 4. Monitor machine "health." Active Side Bearing Temperatures—Monitor for temperature increase.

· turbine case exhaust temperature—200°F max

· blower discharge pressure—monitor

· blower discharge temperature—monitor

· machine vibration—monitor axial movement

· turbine case drains—check for liquid or plugging

· turbine seal steam—maintain at ~2 psig

Step 5. Test the 150 psig steam for baseline conductivity. Obtain sample from bleeder on the strainer blow down line upstream of the trip and throttle valve.

Step 6. *Slowly* start condensate/vinegar solution injection to the steam desuperheating mixer. Reduce the steam temperature at 100°F per hour maximum by increasing the condensate/vinegar injection. *Check turbine case drains often* for liquid accumulation. Continue to monitor machine "health." The machine speed is likely to be less than 1000 rpm (at last cleaning typically ran at 600 to 800 rpm). This is O.K.

Step 7. Sample and test the steam condensate after the surface condenser for conductivity often. Halt the *increase* of condensate/vinegar solution injection when the turbine exhaust condensate conductivity increases (spikes). This conductivity spike indicates deposit removal. Continue to monitor machine "health." When the conductivity falls back to half its peak, resume increasing the condensate/vinegar injection. Again, halt the injection increase at subsequent conductivity spikes. At the last cleaning, the conductivity spikes were difficult to catch. Dirty/dark condensate was observed at the turbine case drains.

Step 8. The acidizing is complete when the steam downstream of the mixer is saturated (~366°F) and the turbine exhaust condensate conductivity is down to 200 micro-mhoms.

Step 9. Repeat steps 5 to 7 injecting straight condensate from TB-1 surface condenser. Throttle the 150 psig steam to the steam desuperheating mixer if necessary to allow injection of he condensate.

Step 10. S/D TB-2, notify the Shift Foreman, and restart with 600 psig steam per the normal start-up procedure as the foreman's orders direct.

Step 11. Repeat the above procedure for TB-1 turbine. The piping will be changed to get 150 psig steam from the turbine drive supply at TB-1 Surface Condenser Condensate Pump and to get condensate from TB-2 Surface Condenser.

An in-place solvent cleaning procedure was developed for removing deposits from the turbine rotor driving the FCCU Air Blower. Using this procedures required only one day of reduced FCCU feed rate, as opposed to the five days typical of mechanical disassembly. The procedure developed for this application was an adaptation of traditional online condensate washes. Modifications to standard procedures include:

• Using auxiliary 150 psi steam, rather than 600 psi drive steam, to reduce risks associated with thermal expansion and contraction.

• Acetic acid was added to the condensate injection to more effectively remove the deposit.

Application of the modified procedure was equally effective at restoring the turbine's rated horsepower as compared with previous mechanical methods and saved four days of full FCCU operation. The turbine efficiency improvement resulting from application of this cleaning procedure was used to increase the FCCU feed rate 2,700 barrel/day.

CENTRIFUGAL COMPRESSOR CLEANING

Hydrogen Systems

Hydrogen is a common product used in most refineries, associated with the hydrogen systems typically, is a recycle compressor or a make up compressor. These compressors can be positive displacement or centrifugal types. The hydrogen systems commonly have chlorides associated with them. The deposition of chlorides is one of the most common deposits found in compressors associated with hydrogen systems. The need for cleaning compressors in these services can vary as the chloride levels change.

Chloride Contamination

The first case that will be discussed is an Elliott 38MB-8 recycle compressor.

- Driver—electric motor/gear
- Horsepower—8000d
- RPM—10,600
- Suction Pressure—95 psig
- Discharge Pressure—325 psig
- Service—hydrogen recycle
  - Ultraformer
  - Five swing reactors
- Hydrogen purity—70 to 82 percent

History

This compressor had traditionally been taken offline for cleaning after six to eight months of service. The recycle stream that this compressor handles has high chloride levels. Three years ago the company installed a naphtha injection quill into the suction pipe. The injection point was three pipe diameters from the suction flange. The rate of injection was set at 3.0 percent by weight of flow. The machine has not shown a reduction in performance or an increase in vibration since the injection was started. Prior to the online injection, the machine was taken offline and cleaned using the following "crank wash" procedure:

Compressor Isolation

- Shut down, block in and purge compressor
- Close suction and discharge valves.
- Depressure compressor through the vent to atmosphere on the discharge line.
- Purge with nitrogen entering the suction side of the compressor and exiting through the atmospheric vent on the discharge side. Purge until exiting gasses test safe.
- Install blinds in the following locations:
  - Downstream of compressor suction block valve (at suction flange)
  - Upstream of compressor discharge check valve
- Remove the balance line. The flange at the compressor suction will be the supply line connection. Install a blind flange at the balance line casing flange.
- Remove the relief valve from the compressor discharge. Blind off the flare side. The compressor side will be used for the return line connection.
- Close the casing drain lines.
- Lube and seal oil system should remain in service to prevent contamination of the oil.
- Install a slow turning (30 to 60 rpm) air operated drive unit on compressor coupling.

Wash Preparation

- Service company is to supply two rigs:
  - A pumper with a 1000 gal tank, and
  - A waste disposal truck
- Bring 500 lb of soda ash and 25 giant size boxes of dish washing compound (2 lb, 3 oz) to the site.
- The tank on the pumper should be cleaned twice by circulating 200 gal of condensate, 100 lb soda ash, and one giant size box of dish washing compound for ten minutes. If upon completion of the second wash, the wash solution is not water-white, the tank must be washed again.

Compressor Wash

- To 1000 gal of condensate, add 150 lb of soda ash and 11 giant size boxes of dish washing compound.
- Run a chloride analysis on a sample (qt) of the wash solution. The results will be used in monitoring the wash as the wash proceeds.
- Connect the wash solution supply line (2.0 in) to the balance line flange on the suction of compressor.
- Connect the return line (2.0 in) to the compressor side of the relief valve opening on the discharge of compressor. It is desirable to circulate counter flow to rotation of compressor. The immediately preceding two steps may be switched so as to reverse the supply and return line connection locations.
- Make sure casing drain lines are closed.
- Open a high point vent.
- Inject the wash solution at a rate of 30 to 50 gpm. CL = ________________.
- When the compressor is filled with wash solution, close the high point vent and begin rotating the compressor (30 to 60 rpm).
- Circulate for two hours at _________°F
- When circulation has stopped, continue rotating compressor.
- Empty the holding tank to the waste disposal truck. When the truck is full, a quart sample from each tank compartment must be taken before the solution can be dumped into the impoundment basin. The volume, pH, and time of disposal must be recorded.

Vol.________ ph_______ CL______ Time_______

- Flush the holding tank with 300 to 400 gal of condensate.
- Make up a second 1000 gal of wash solution (1000 gal condensate plus 150 lb soda ash plus 11 giant size boxes dish washing compound.) Pull a quart sample for chloride analysis. CL ______ . While circulating the second batch of wash solution, pull a quart sample every 30 min for immediate chloride analysis. When the level of chlorides has not changed by more than ±20 ppm for three consecutive samples, the compressor is clean. Circulation and rotation of the compressor can be stopped. Record analysis results on a separate sheet of paper.

• Drain as much solution as possible back to the holding tank. Drain the remaining liquid from the compressor through the casing drains.

• Empty the holding tank into the waste disposal truck. Handle the disposal of this material the same as the first batch was handled.

Rinse Procedure

• Keep same piping connections.

• Open casing drain lines.

• Fill the tank (100 gal) with condensate.

• Begin injecting the condensate at a rate of 100 gpm, then begin rotating the compressor (150°F condensate).

• There will be very little return to the tank. Most of the condensate will drain through the drain lines. The water will initially have coke in it. As the coke is flushed from the compressor, the orange tinge of the rinse solution will be noticeable. Some of the drains may have to be pinched to allow flow through all the drains.

• The compressor should be rinsed with a minimum of 1000 gal of condensate. When the coke is no longer visible in the rinse water, the rinse is complete. Stop circulation and rotation of compressor.

• Drain compressor through the casing drain lines.

• Any extra condensate can be taken to the storm sewer.

Platformate Rinse

• Prepare a solution of 1.0 gal of kontol K-602 and 100 gal of platformate in two clean 15 gal drums.

• Disconnect the wash/rinse supply and return lines.

• Make sure drain lines are closed.

• Using an injection pump, fill the compressor with the platformate solution.

• Rotate the compressor for 30 min.

• Drain the compressor through the casing drain lines. Add water to the drain trough while draining the platformate solution.

Drying Procedure

• Use nitrogen to purge and dry the compressor by venting the vapor to the atmosphere and the liquid to the drain.

Reciprocal Compressor Wash

Some hydrogen systems do not have CCR systems that allow continuous regeneration. These units require shutdowns to regenerate the catalyst. The recycle compressor is used during the regeneration process, after the regeneration process is complete the compressor required cleaning. This cleaning process is very common to centrifugals. The authors have used a water wash procedure for reciprocal compressors in a similar service.

The procedure was very simple:

• Spread the discharge flange and open the discharge bottle drains.

• Hook up condensate to the suction nozzle of the compressor.

• Start the compressor.

• Open the condensate at a very slow rate until a slight liquid flow is noted at the discharge. Be careful not to adjust the flow too much.

• Wash until the liquid (water) gets clear.

• Shut off water until dry then repeat step four. Repeat this step until water is clear.

• Disconnect condensate line and shut down machine.

• Purge with nitrogen and return to service.

This was a procedure that was developed for four throw CMA reciprocal; compressors in a hydrogen system in a motor fuel unit. This procedure replaced the need to overhaul the four reciprocal compressors saving both down time and expense.

Ammonia Contamination

Chlorides are not the only culprit that contaminates compressors in hydrogen services. An Elliott 20MB9 compressor is used as a hydrogen recycle compressor in a diesel hydrotreater. After nine months of uneventful operation the unit performance dropped due to what appeared to be fouling. The first indication of fouling was the reduction in flow and head. This machine is equipped with magnetic bearings as the machine became severely plugged the thrust bearings began to react to the load changes. Being able to monitor thrust and radial load changes allowed continued operation of the machine for approximately one month after the first initial indication of the plugging. The compressor was shut down and crank-washed to remove the buildup. Assuming the problem was chlorides, an injection system was installed. In less than one month, the compressor fouled so bad it had to be disassembled and mechanically cleaned. Analysis of the deposits found ammonia salts were being formed as a result of a high ammonia and chloride level in the hydrogen stream. In this case, the on stream injection appeared to add to the build up problem.

There had been a catalyst change just prior to the initial fouling problem. The new catalyst was a different composition and generated higher levels of ammonia. The rules of the game had changed without both sides knowledge. Now that the contaminant was defined, the problem would be to reduce the amount of ammonia or chlorides that were causing the deposition in the compressor. Operations was assigned this project. The injection system was removed, posthaste. In the meantime, Maintenance developed an offline washing procedure to clean the machine without disassembly.

The washing procedure will be carried out by a service company with Technical Service department supervision. Two wash steps will be performed. Each step consists of an initial 20 min rinse with condensate followed by a 45 min wash using a 5000 gal condensate/75 lb soda ash/13 lb dish washing compound mixture. Following the second wash, the compressor will be rinsed with condensate twice for 15 min each. The entire washing procedure will take approximately three hours. Refer to Figure 8 for the piping schematic used for this procedure.

Preparation

• Hook up nitrogen trailer to dry gas seal auxiliary buffer.

• Install blinds in suction and discharge lines (see drawing).

• Remove ¾ in valve assembly on suction line. Hook up water wash connection to 2.0 in flange.

• Remove spool piece from buffer gas line. Hook up return water wash connection to existing 2.0 in valve on discharge line.

• Remove balance piston line and blind.

• Remove coupling guard and spacer.

• Install adapter plate to coupling hub.

• Verify correct rotation.

• Levitate rotor.

• Start buffer to both seals at 30 scfm per seal. Vent lines (primary and secondary) are to be open to atmosphere.

• Rotate compressor.

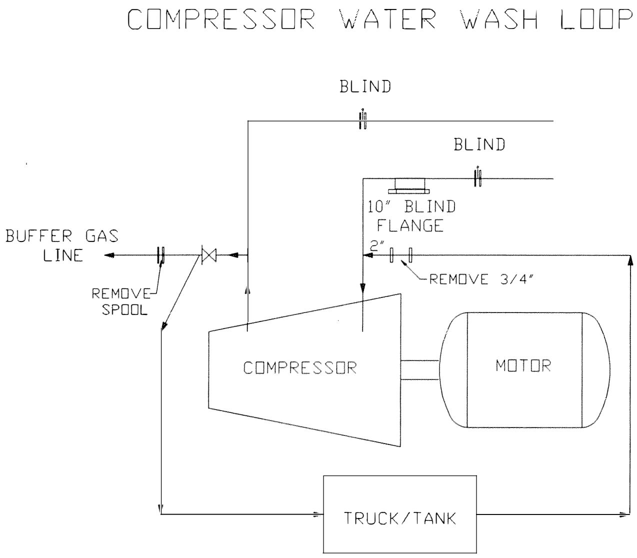

Figure 8. Piping Schematic for Offline Water Wash of Hydrogen Recycle Compressor.

First Wash

- Fill system with condensate and circulated for 20 min. Occasionally open belly drains while circulating. Sample water for chlorides before circulating, after 10 min, and after circulation is completed. Drain compressor through belly drains.
- Refill system with 500 gal condensate/75 lb soda ash/13 lb dish washing compound mixture and circulate for 45 min.
- *Note*: Nitrogen will be present on return leg of wash.
- Periodically open and close all belly drains to prevent plugging.
- Technical Services will monitor chloride levels.
- Drain mixture through belly drains.

Second Wash

- Repeat first wash.

Rinse

- Rinse with condensate twice for 15 min each. Drain through belly drains between rinses. Pump remaining condensate through compressor to sewer. Sample final rinse for chlorides.
- After second rinse, disconnect wash piping and drain the compressor.
- Loosen 10 in blind flange on suction line to drain any remaining water.
- Purge with nitrogen.
- Pump 30 gal of reformate and 1.0 pint kontol inhibitor while rotating the compressor for 20 min.
- Drain the compressor.
- Purge with nitrogen four hours minimum fluoroscint seals.
- Replace piping and return the compressor to Operations.

Both cases discussed in this section demonstrate the need for cleaning without disassembly. One machine demonstrates that online injection helped keep the machine online. The other case noted similar symptoms in a hydrogen service compressor, but the addition of ammonia made the injection system a detriment instead of the benefit it is on the other hydrogen compressor. One must make sure that he has all the facts before proceeding with a cure. Even if the offline cleaning has to be performed, the expense and downtime is still a lot less than operating at reduced capacity and eventually having the unit trip and having to replace damaged parts. Online injection systems are also successfully used on three other compressors in cat cracker wet gas and coker wet gas services.

CLEANING AXIAL COMPRESSORS

Axial Compressor Performance

For simplicity, the discussion of cleaning axial compressors is limited to air machines with atmospheric inlet, since these applications are the overwhelming majority. Axials are used in place of centrifugal compressors when relatively large volumes of air are required, at low to medium pressure rise, e.g., FCC, steel mill, and air separation blowers. In addition to having a higher flow coefficient , axial compressors, especially with variable stator vanes, are better suited to constant head, variable flow applications, particularly FCC service.

A big advantage of axial compressors is that they are usually more efficient than centrifugal compressors. In simplified terms, the higher efficiency is because axial compressors require less changes in direction of the gas going through the compressor than centrifugal compressors. The Euler equation shows that head rise is obtained by changing gas velocity through a compressor stage. The changes can be radial, tangential, or relative. By nature, centrifugal compressors obtain most of their head rise through a change in radial velocity. Radial change is the most effective means to maximize head rise in a single stage, but since it requires a 90 degree change in gas direction it is difficult to do efficiently. Axials do not change the radial velocity of the gas; they obtain the same head rise by changing tangential and relative components of gas velocity. This results in a more efficient means of compressing the gas, but requires more stages. Obtaining efficient gas compression in axial compressors requires closely spaced blading at precisely set angles to maintain as-designed gas velocity vectors throughout the compressor. The downside is that axial compressor staging is more affected by upstream flow deviations than centrifugals. Because of this sensitivity to stage mismatching, axial compressors are more difficult to design and more critical to maintain in peak, as-designed condition.

Effects of Fouling

Axials require thin, cantilevered blades that are more vulnerable to damage from solid and liquid particles in the gas stream than centrifugal impellers. Erosion, impact, and heavy buildup effect blade stresses and frequencies, and could lead to blade failure. The thin, airfoil design also makes them more susceptible to performance degradation due to buildup of these particles on the blades. The sensitivities of axial compressors to disturbances in flow make it imperative to have clean inlet air. Fouling on axial blades causes both a blockage and a disruption of the streamlines at the aerodynamic surfaces. The blockage effect restricts flow by narrowing the passage areas within the gaspath of the compressor. This is similar to the effect fouling has on centrifugal compressors and turbines. The blockage reduces flow and discharge pressure by causing an additional pressure loss in the system. To offset this, the vanes are opened farther on variable-vane machines, or the speed is increased on fixed-vane units.

The disruption of the flow on the aerodynamic surfaces due to buildup has more of a negative effect on axial performance than on centrifugal compressors and turbines. Similar to icing on an aircraft wing, fouling causes the flow to separate from the surface causing loss in lift and pressure rise. Obviously, an aircraft wing has a more severe result from this effect, but the physical principles are the same. In a multistage axial, the loss of boundary layer at one stage effects performance of subsequent stages. The loss of boundary layer leads to turbulence behind the blade, that in turn causes an increase in the deviation of the discharge air angle. This deviation causes an increased incidence at the inlet of the following vane that can continue through the remainder of the compressor stages. This is why axial compressors require more attention to gas cleanliness.

Light compressor fouling also can lead to mechanical blade damage by causing a stalled condition. When the surge control system is correctly set, it is set for the clean blade condition. The blockage effect of fouling will normally cause the compressor to act as a smaller flow design, thus increasing the surge margin. But, the effect of fouling on the aerodynamic surfaces can cause the blades to stall at a higher flow than the design value. If the surface effect is greater than the blockage effect, it is possible for the unit to be operating in rotating stall, or even surge, without the surge control system detecting it. Rotating stall can set up a forcing frequency that may be in tune with a blade frequency. This is a rare phenomenon, but the user should be aware of the possibility.

Preventive Measures

Inlet air filtration for axial compressors should be designed to remove 99 percent of particles sized above 10 microns. This requirement not only protects the compressor from performance degradation due to fouling, but also prevents mechanical damage to the blades due to erosion, impact and heavy buildup. Prevention of mechanical damage is the primary reason for requiring good inlet filtration, but prevention of light buildup that effects aerodynamics is a close second.

Besides meeting a filtration rating of ten microns, the user should take additional precautions to insure a clean compressor. The inlet filter housing should be located well above ground level to minimize ingestion of dust stirred up by traffic or other activity. Location of the filter also should consider the location of exhausts from other processes, e. g., ESP for the FCC exhaust, steam vents, chemical fume emissions, etc. The filter housing should have rain baffles to prevent direct intake of liquid into the unit. Consideration also must be given to the inlet shaft seal. For designs using integral bearing housings, the shaft seal should be buffered to prevent drawing oil and vapors into the unit. Even with separate bearing housings, the user should request provisions for inlet seal buffering in case of future problems. Also note, some axial air compressor designs incorporate a midstage takeoff for buffering the discharge seal to prevent hot discharge air from contacting the bearing housing. This same buffer source also can be used for inlet shaft seals.

Blade coatings should be considered for installations in humid areas with corrosive elements (e.g., HCL, H_2SO_4, salt air, etc.). This is only necessary on the first few stages, where condensation is a possibility. A combination coating is recommended, with a protective, aerodynamically smooth outer coating and a sacrificial galvanic inner coating. This type of coating offers corrosion protection and some erosion protection. Also, the smooth surface makes it more difficult for foreign material to adhere and build up.

When to Clean

With adequate inlet filter system and shaft sealing an axial compressor is slow to foul; changes in performance would usually be imperceptible. Fouling often goes unnoticed until hot days, when at full production the axial cannot deliver the flow it once did. If maintenance personnel are unfamiliar with the machine or the effects of fouling, they often call in the OEM service representative, stating only that the unit has performance problems. The representative arrives, determines the likely cause of the problem, and pours a $2.00 box of rice in the inlet. The unit comes back to full production, the representative hands the user a bill for time and expenses, then he goes home. This expense and lost revenue can be avoided by taking proper preventive measures.

Knowing the problems that can occur from fouling, it is best to know the machine, and take action early. Performance trending is the recommended method to determine when the unit is beginning to show performance deterioration. This procedure can be as simple as a weekly log of basic parameters (Table 1) that would show the trends of flow and pressure ratio adjusted for inlet conditions and vane setting (see Gresh, et al., for more information on performance trending [1]). Trending information also could be tracked by computer, such as a DCS system or local monitoring system.

Table 1. Sample Data Sheet for Recording Performance Trending.

DATE			
P_{bar} - PSIA			
RH - %			
P_{in} - PSIA			
T_{in} - °F			
P_{out} - PSIA			
T_{out} - °F			
Flow Δ P - PSI			
Vane Position			
Speed - RPM			

Whatever performance trending method is used, most important is that someone is specifically responsible for recording the data, has knowledge to analyze it, and takes action when the unit needs cleaning. The user should work with the OEM to set cleaning requirements.

Online Cleaning

Even with a properly designed and maintained inlet filter system, an axial compressor can still suffer buildup on the blades or stationary surfaces within the aeropath. Over time, small particles consisting of catalyst fines, dust, humidity, petroleum vapor or other chemical fumes can foul the unit. When a proper preventive program is in place, this situation will be identified before it can cause an operational problem. Any change in speed, flow, or pressure should be treated as fouling. Cleaning is quick and inexpensive, and, even when fouling is not the cause of performance problems, it does no harm. As part of the preventive program, each cleaning event should be logged with immediate before and after parameters. Logging will help identify serious problems that require more in-depth cleaning than can be done online.

Obviously, a problem is more serious than mere fouling when change in performance is sudden and drastic, such as severe decrease in throughput, or tripping the unit. A box of rice cannot remove a ton of catalyst that backed into the discharge casing.

When severe situations occur, it is best to contact the OEM; deadheading an axial compressor will break blades and distort the housing.

The user has several choices when it is determined that the unit needs to be cleaned. The most common online method is an organic abrasive, such as rice or crushed walnut shells. For units with coated blades, an online liquid wash is recommended. If these methods are not effective, an offline cleaning is necessary. This requires removing the rotor and hand cleaning the rotor blades, stator vanes, and gas passages. Variable-vane axials should not be crank washed , i.e., slow rolled with a partially flooded casing. Besides the obvious problem of water leaking through the variable vanes, dirt from the flowpath could settle in the variable-vane bushings, causing them to bind. It is recommended that the compressor OEM be contacted to discuss the problem when online cleaning methods do not work.

Organic Abrasives

Ricing is the generic term for online cleaning using organic abrasives, whether rice or walnut shells are used. When the organic material is compatible with the process, this is a common method of easily and effectively cleaning axial and centrifugal compressors. Ricing is also used to clean other types of machines, such as IC and diesel engines, and reciprocating compressors. Most axial compressor applications involve supplying atmospheric air to a combustion process, so the organic material is burned up after cleaning. When in doubt, consult Process Engineering about compatibility of ricing with the process. Four general steps to ricing an axial compressor follow:

Step 1. Find a suitable location in the inlet piping where a 1.0/2.0 in ID funnel or tubing can be inserted. The connection should be close to the inlet with sufficient velocity to entrain the abrasives and enough run to get a fairly uniform distribution before entering the compressor. There should be no areas between the connection and compressor where abrasives could drop out of the air stream, either from obstruction or low velocity.

Step 2. During the cleaning procedure, an operator should monitor flow, and discharge pressure and temperature. Another operator should monitor vibration. If there is significant rise in vibration, stop the cleaning to assess the situation, determine the source, and correct the vibration problem. Call the OEM for advice if necessary. Note also, cleaning can cause a sudden opening of blocked passages, resulting in a quick change in performance. Ensure that the surge control system is operating and the process can handle a sudden increase in flow.

Step 3. If the inlet is above atmosphere, a forced injection method is used, but, such installations are beyond the scope of this paper. This ricing procedure assumes a slightly subatmospheric inlet. Using either uncooked rice or crushed walnut shells (maximum diameter 0.25 in), feed the abrasive through a funnel or a tube at a steady rate into the unit. The nominal feed rate should be 0.5 lb/min/100,000 cfm; but, check with the OEM for the rate recommended for the particular compressor being cleaned.

Step 4. Five pounds of abrasives are usually adequate to return a unit to normal operation. The cleaning process is complete when the operator notes that performance has returned to normal and no additional improvement is gained by continued ricing. But, when no significant improvement is seen after feeding 5.0 lb of abrasive, the operator should make sure the abrasive is going through the machine and not dropping out before it reaches the inlet. If the abrasive is traveling completely through the unit, try another cleaning cycle. If rice was used for the first cleaning, try walnut shells the second time, since they are a little more abrasive. When a second cleaning is not effective, contact the OEM to determine if another online method could be used. The performance degradation may be severe enough to warrant shutdown of the unit and offline cleaning prior to the next scheduled turnaround.

Ricing is easy and inexpensive, which makes it adaptable with scheduled cleaning cycles. Feeding a pound or two of abrasives through the compressor once a month can prevent buildup from reaching the point where offline cleaning is required. Yet, this does not replace the need for logging compressor performance, awareness of unit performance, and comparing unit performance to an as-clean baseline.

Liquid Wash

Coating vendors often do not recommend ricing compressors with coated blades. The most common online method of cleaning coated blades is a water spray, using an aqueous cleaning solution especially designed for this application. This method is commonly used on gas turbines, both aircraft and land based. On industrial axial compressors, the liquid is injected at high pressure through atomizing nozzles in the inlet casing. The liquid wash can be automated to clean at programmed intervals, an obvious advantage, but should not cancel the need for performance trending. If buildup is occurring in spite of liquid washing, performance trending will alert the operator before it becomes a major problem.

Followup

Online cleaning is effective in cleaning light surface buildup. It should be done regularly, since it is quick, inexpensive, and harmless to most axial compressor applications. However, there are problems that online cleaning will not solve, such as sticky buildup due to oil vapors mixing with foreign material, or materials baking onto the blades in the hot rear stages of the compressor. Buildup resistant to online cleaning methods requires manual cleaning of the blades. Performance degradation also can be caused by increased blade tip clearance due to rubs during surge or high vibration excursions. Another cause can be guide vanes being out of position, either as a row or individually. When individual vanes are out of position, the problem must be addressed immediately, since the adjacent rotor blades may have natural frequency response at that vane passing frequency, or at the first or second harmonic of it.

When performance declines, the first step is online cleaning of the axial compressor. If cleaning is ineffective, the compressor OEM should be consulted for the appropriate action. The important point is that the user must know the machine; if normal operation is unknown, then abnormal operation may not be identified until the process has to be shutdown to fix the problem.

RISKS IN CLEANING TURBOMACHINERY

Online and reduced speed cleaning of turbomachinery requires care and thoughtful planning to ensure all contingencies are considered and emergency plans are in place in case of problems. The coordination between user and OEM cannot be over empathized. The equipment can be operating in an off-design condition during cleaning, and if all possibilities are not considered, damage may occur. This is particularly applicable to online cleaning of turbines, where problems could arise from thermal gradients, slugs of water forming, salts cleaned from inlet piping or front stages causing blockage in rear stages or high vibration from nonuniform salt removal. OEMs may have different recommendations for cleaning their turbomachinery. An example of different procedures recommended for different units would be the two cases shown herein for cleaning turbines. The turbine cleaned online was to be brought back to full speed in case of loss of condensate during cleaning. The OEM for the turbine cleaned offline recommends tripping the unit in case of loss of condensate.

Similar forethought must be given to cleaning process compressors. For example, the rule of thumb of 3.0 percent of mass flow for determining the amount of liquid spray works for most applications, but may have an adverse effect on high density gas processes. The combination of 3.0 percent liquid spray and build up may clogged the relative small passages of dense gas machines. In cases of high pressure and/or high mole weight gas, the OEM might recommend a smaller amount of liquid spray.

This presentation is to share the experiences of applying general cleaning procedures to specific situations. It is not meant to replace the consideration, coordination, and planning needed to develop specific procedures for cleaning the reader's turbomachinery.

CONCLUSION

Maintaining turbomachinery performance is critical for efficient operation of the process. Fouling caused by contamination, condensation, corrosion or chemical reaction lowers the head and flow capabilities of compressors, and lowers the power output of steam turbines. Reasons were discussed for keeping turbomachinery clean, types of fouling, and methods to clean compressors and turbines when fouling occurs. It is very important that the user works with the OEM to correct fouling problems. The OEM knows the risks in operating turbomachinery in a fouled condition, along with the most suitable method to clean the unit. Also, the OEM can be helpful in identifying the cause of the problem, whether corrective action needs to be taken, and what kind of action is appropriate. Every turbomachinery application is different, and problems should be analyzed to ensure that the cause is identified and proper action is taken. Quick fixes may work temporarily, but could cover up a potentially severe problem in unit operation. An example would be a frequent need for ricing a FCC axial air blower. Ricing is a fairly innocuous procedure, but if this type of unit, normally having a 10 micron inlet filtration, keeps fouling over a short period of time, the cause needs to be investigated.

Hopefully, the presented case histories of the steam turbine and process compressor will aid the reader in similar situations. Important points the authors would like to leave with the reader are:

- Maintaining a clean flowpath in turbomachinery is important to its effective performance and, users must know the normal (as-designed) condition of their turbomachinery to employ as a baseline for detecting changes in performance.
- A performance trending log should be kept on critical turbomachinery so deterioration in performance can be identified as early as possible.
- If fouling does occur, the root cause should be identified, even if it is later determined necessary only to treat the symptoms.
- The user should work with the OEM to know the risks of operating the turbomachinery in a fouled condition, to find the best way to clean the unit, and to determine the cause of the fouling and corrective action needed.

REFERENCE

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